FLOW QUALITY MEASUREMENTS
IN COMPRESSIBLE SUBSONIC FLOWS

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Until recently, very few hot-wire measurements were reported for subsonic compressible, transonic, and low supersonic flows. There are several reasons for this. First, for a given probe, the heat transfer from a heated wire oriented normal to the flow is a function of the three fluid variables: velocity, density, and total temperature. This makes the calibration of the hot-wire probe very time consuming. Also, since the heat transfer from the hot wire is a function of the combined effect of these three fluid variables, it is difficult to separate the individual effects of these variables. Finally, the dynamic pressures in these speed ranges are high and wire breakage can be excessive due to aerodynamic loads and, of course, any particles in the flow can cause wire failure.

Before the development of the three-wire hot-wire probe (fig. 1, refs. 1 and 2), the application of hot-wire anemometry to compressible subsonic and transonic flow was similar to that existing in high supersonic flow. In this earlier application, the heat transfer from hot wires was considered to be a function of mass flow and total temperature (i.e., two-parameter method) rather than the individual quantities of velocity, density, and total temperature. The results using a two-parameter method made the calibration of hot-wire probes and data reduction somewhat less complex, and fluctuating quantities using this technique have been reported for compressible subsonic, transonic, and low supersonic flows. The two-parameter method represented an advance in hot-wire anemometry and renewed interest in the problems encountered in making such measurements in these flow regimes. However, the two-parameter method requires several restrictive assumptions and required additional measurements to obtain quantitative flow quality results. In contrast, the three-wire hot-wire probe technique requires only the assumption usually made for hot-wires anemometry with small perturbations (refs. 1, 2, 20, and 21).

The purpose of this paper (fig. 1) is to: (1) re-examine the heat transfer from a hot-wire probe in the compressible subsonic flow regime, (2) describe the three-wire hot-wire probe calibration and data reduction technique used to measure the velocity, density, and total temperature fluctuations, and (3) present flow quality results obtained in the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) and in flight with the NASA JETSTAR from the same three-wire hot-wire probe.

- Compare wind tunnel and flight measurements with same probe and data reduction technique

- Langley 0.3-meter transonic cryogenic tunnel flow quality (8 by 24-in. test section)

- Jet Star flights at Dryden to obtain atmospheric turbulence (over Mojave Desert)

- Three-wire hot-wire probe method:

    - No restrictive assumptions — such as used with the single wire technique

    - Data reduction technique separates velocity, density and total temperature fluctuations

GENERAL HOT-WIRE EQUATIONS

The mean voltage measured across a given hot wire, oriented normal to the flow, is a function of velocity, density, total temperature, and wire temperature. The total change in the mean voltage due to a change in the independent variables can be obtained from the calculus. If a constant temperature hot-wire anemometer is used, $dT_w = 0$ within the limits of the ability of the feedback amplifier to hold the temperature of the wire constant. The equation for the fluctuating quantities and the definitions of the three sensitivity coefficients are given in figure 2. Attempts usually are made to solve this equation by using the mean square values of e'. However, this method results in an equation with six unknowns. The squared equation can, in principle, be solved by operating a single wire at six overheats and solving a system of six equations for the six unknowns. However, when this was tried, difficulties were encountered inverting the 6 x 6 matrix.

$$E = f\left(u, \ \rho, \ T_t, \ T_w\right)$$

$$\left(\frac{e'}{E}\right) = S_{\overline{u}}\left(\frac{u'}{\overline{u}}\right) + S_{\overline{\rho}}\left(\frac{\rho'}{\overline{\rho}}\right) + S_{\overline{T}_t}\left(\frac{T'_t}{\overline{T}_t}\right)$$

$$S_{\overline{u}} = \left(\frac{\partial \log E}{\partial \log \overline{u}}\right)_{\overline{\rho}, \ \overline{T}_t, \ T_w}$$

$$S_{\overline{\rho}} = \left(\frac{\partial \log E}{\partial \log \overline{\rho}}\right)_{\overline{u}, \ \overline{T}_t, \ T_w}$$

$$S_{\overline{T}_t} = \left(\frac{\partial \log E}{\partial \log \overline{T}_t}\right)_{\overline{u}, \ \overline{\rho}, \ T_w}$$

Figure 2

EQUATIONS FOR THREE-WIRE HOT-WIRE PROBE

The form of the general hot-wire equation in figure 2 suggests that the instantaneous values of u', ρ', and T_t can be obtained from the solution of an equation with three unknowns. The means used for obtaining a solution for the three instantaneous quantities was to fabricate a single probe with three hot wires normal to the flow, with each wire operated at a slightly different overheat. Then an equation can be written for each of the three wires as shown in figure 3 and the set of three equations can then be solved for the three unknowns, u', ρ', and T_t', as a function of time. Prior to the solution of the sets of equations, the sensitivity coefficients must be determined from a calibration which uses the measured values of E, u, ρ, and T_t (ref. 2). Once the fluctuating quantities are obtained conventional statistical techniques can be used to obtain mean and root mean square (RMS) values, auto correlations, cross products, spectra, etc.

In principle, the ability to obtain fluctuating quantities using the three-wire hot-wire probe technique can be extended into the transonic and low supersonic flow regimes without difficulty except those typically associated with lengthy calibration and possible wire breakage.

$$\left(\frac{e'}{E}\right)_i = S_{\bar{u},i}\left(\frac{u'}{\bar{u}}\right) + S_{\bar{\rho},i}\left(\frac{\rho'}{\bar{\rho}}\right) + S_{\bar{T}_{t,i}}\left(\frac{T_t'}{\bar{T}_t}\right) \quad i \text{ (hot wires)} = 1, 2, 3$$

$$u', \ \rho', \ T_t', \ \dot{m}' \quad \text{(instantaneous values)}$$

$$\overline{u'\rho'}, \ \overline{u'T_t'}, \ \overline{\rho'T_t'} \quad \text{(mean of cross product terms)}$$

From instantaneous values statistical values are determined

$$\tilde{u}, \ \tilde{\rho}, \ \tilde{T}_t, \ \tilde{\dot{m}}, \text{ etc}$$

Figure 3

THREE-WIRE HOT-WIRE PROBE

The hot-wire probe which was used to obtain flow quality data in the 0.3-m TCT and in flight with NASA JETSTAR is shown in figure 4. The probe was fabricated with six "needles" made from piano wires which were used to mount the three hot wires normal to the flow. The needles, which were about 1 inch long, were glued into a section of six-hole ceramic tubing. The ceramic tubing, with the needles and lead wires, was glued into a section of 0.250-inch stainless-steel tubing. Platinum-coated tungsten wire having a diameter of 0.0004 inch was mounted between the tips of the needles with about 1/4 circle slack in each wire. The wires were about 0.10 inch long and about 0.040 inch apart. Each of the three wires on the probe was operated with its own constant temperature hot-wire anemometer and signal condition system.

For the wind tunnel test, the hot-wire probe was mounted in the 8- by 24-inch test section of the 0.3-m TCT, (both floor and ceiling 5 percent open), in a mounting position normally used for the drag rake. The sensing elements were located midway between the centerline of the tunnel and the ceiling at an axial position approximately at the center of turntables which were usually used to hold two-dimensional models. A shorting probe with three low resistance wires attached to pairs of needles was positioned below and rearward of the active probe. The shorting probe with leads going to the anemometer was used to balance out any lead resistance changes which occurred due to changes in ambient temperature. The resistances of the shorting probe and leads were matched to those of the active probe and both sets of leads followed the same path from the tunnel test section to the anemometers in order to ensure that each set of leads was subjected to the same temperature environment. The shorting probe was used to balance out any lead resistance changes which occurred due to changes in temperature during the test program. This procedure was followed during the wind tunnel (ref. 2) and flight tests.

Figure 4

VELOCITY, DENSITY, AND TOTAL TEMPERATURE FLUCTUATIONS FROM
0.3-M TCT USING THREE-WIRE HOT-WIRE PROBE

The RMS values of the velocity, density and total temperature, normalized by their respective mean values (fig. 5) were calculated from the large amount of detailed data taken during the calibration of the three-wire hot-wire probe. The calibration of the three hot wires (ref. 2) (to obtain wire sensitivity coefficient indicated in figs. 2 and 3) was started at a condition of maximum dynamic pressure (V_∞ - 747 ft/sec, p_t - 48 psia, and T_t - 504°R). The three wires were operated at overheat ratios of 1.6, 1.8, and 2.0). A square wave signal was used to set approximately equal time constants for the three wires. The upper frequency response of the hot-wire anemometry system was about 20 kHz. During the calibration, the velocity was varied from 747 to 220 ft/sec in five even increments with the mean and fluctuating voltages recorded on line at each velocity. In addition, the fluctuating voltages were recorded on odd-numbered tracks of a seven-track tape recorder. As the velocity was reduced, the total pressure was decreased to maintain a constant density at this fixed total temperature condition. The density was reduced in three steps with a similar velocity variation for each of the density steps. The same procedure with varying velocities at constant density was repeated for total temperatures of 522°R and 540°R.

This constant parameter method of calibration, which is a cumbersome procedure, is not required if the multiple linear regression technique is used to obtain the sensitivity coefficients. However, the constant parameter method is useful for determining the form of the correlation equation to be used for the multiple regression method (refs. 2, 20, and 21).

The three sets of fluctuating quantities (fig. 5) were obtained from the simultaneous solution of the hot-wire equation in figure 3 for the three hot wires. The data indicate a significant increase in $\tilde{u}$, $\tilde{\rho}$, and $\tilde{T}_t$ with increasing unit Reynolds number for a given Mach number and also indicate an increase with increasing Mach number. In general, the velocity and density fluctuations are quite high and have maximum values of about 7.5 and 8.4 percent, respectively. The total temperature fluctuations, which have maximum value of about 0.57 percent, are approximately an order of magnitude lower than velocity and density fluctuations.
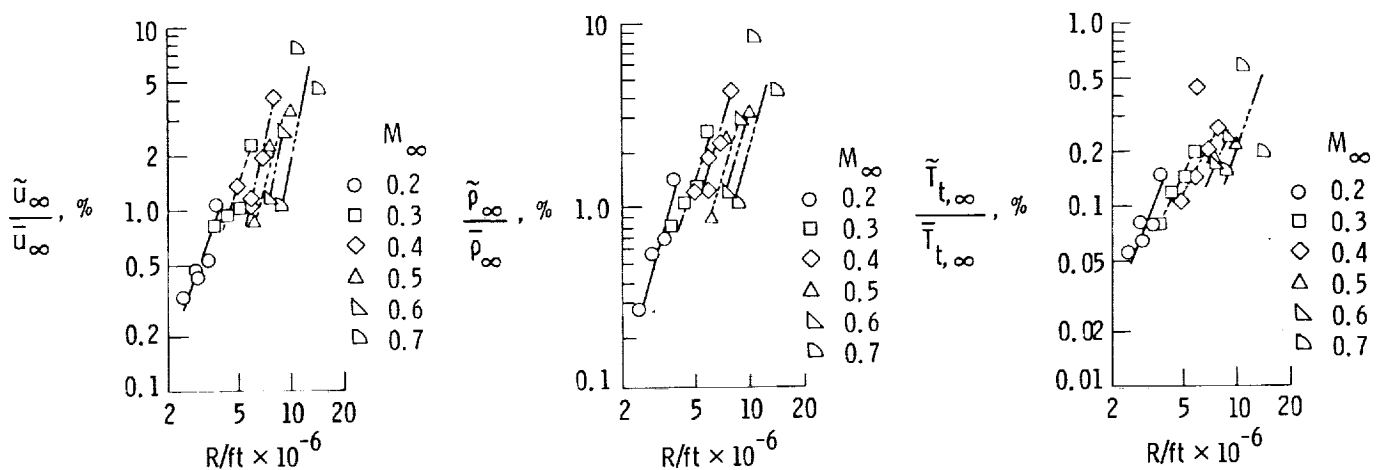

Figure 5

MASS FLOW FLUCTUATIONS FROM THREE-WIRE HOT-WIRE PROBE DATA

In the past, mass flow fluctuations were often used to infer wind tunnel disturbance levels in a manner similar to the way velocity fluctuations (as shown in fig. 5) were used to quantify wind tunnel disturbance levels. However, the mass flow fluctuations are about an order of magnitude lower than velocity fluctuations at the higher Mach numbers and Reynolds numbers. An example of this can be seen from the calculation of the normalized mass flow fluctuations (fig. 6) from the same three-wire hot-wire probe data that were used to determine the velocity and density fluctuations in figure 5. The mass flow RMS fluctuations were calculated from the sum of the instantaneous velocity and density values. The maximum value of the mass flow fluctuations is about 0.78 percent compared to a maximum value of 7.5 percent for the velocity fluctuations at the same conditions. The reduction in the mass flow fluctuations is predominately due to the fact that at high subsonic Mach numbers the major disturbances in the test section were due to upstream propagation of sound from the diffuser. For these conditions, the velocity and density fluctuations are anti-correlated, with a correlation coefficient nearly equal to -1.0, thereby resulting in a lower value for the mass flow fluctuations (refs. 2 and 4).
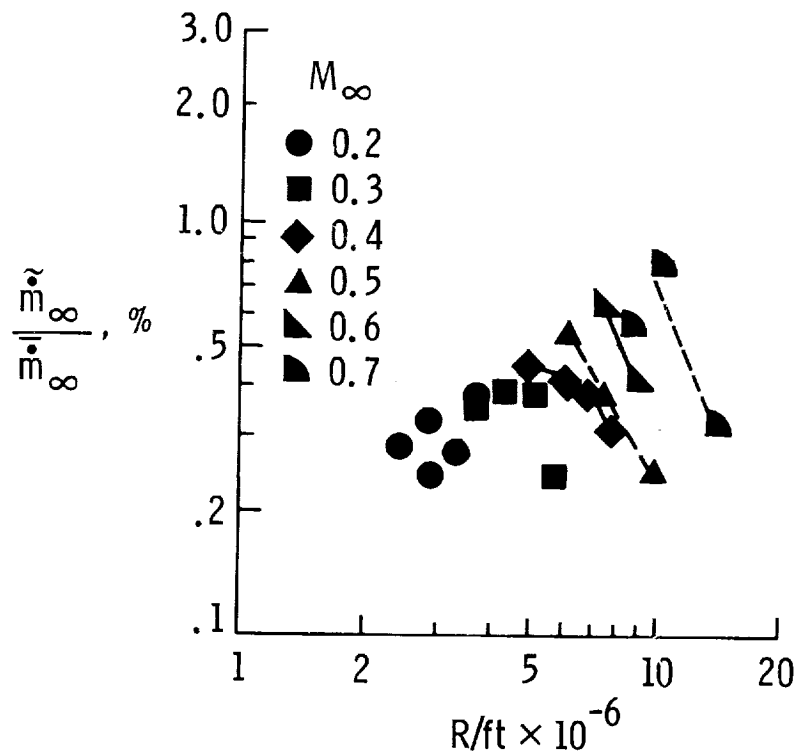
Figure 6

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Flight tests, which were conducted at the Dryden Flight Research Facility, using the Lockheed JETSTAR were made with the same three-wire hot-wire probe used in the 0.3-m TCT tests (figs. 4, 5, and 6). A photograph of the NASA JETSTAR (fig. 7) indicates the location of the hot-wire probes on the leading edge on the left-hand portion of the wing.

Three-wire hot-wire probes

Figure 7

CLOSE VIEW OF THREE-WIRE PROBES MOUNTED ON LEADING EDGE OF JETSTAR WING

A closeup view of the probes (fig. 8) indicates the type of installation used to mount the three-wire hot-wire probe holders on the leading edge of the wing. The dummy probe was mounted nearer to the fuel tanks where possible flow interferences could occur. The active probe was mounted in a more outboard position, in what was considered to be a more interference-free flow field. Note that when this photograph was taken, the leading-edge flap was lowered to facilitate the installation of the two probes on the leading edge of the wing.

The dummy probe, or shorting probe, contained three low resistance wires across the three pairs of needles. This probe was used to balance out any change in lead resistance due to ambient temperature changes, in the aircraft. A similar procedure with a dummy probe was used during the flow quality test in the 0.3-m TCT (fig. 5 and ref. 2).
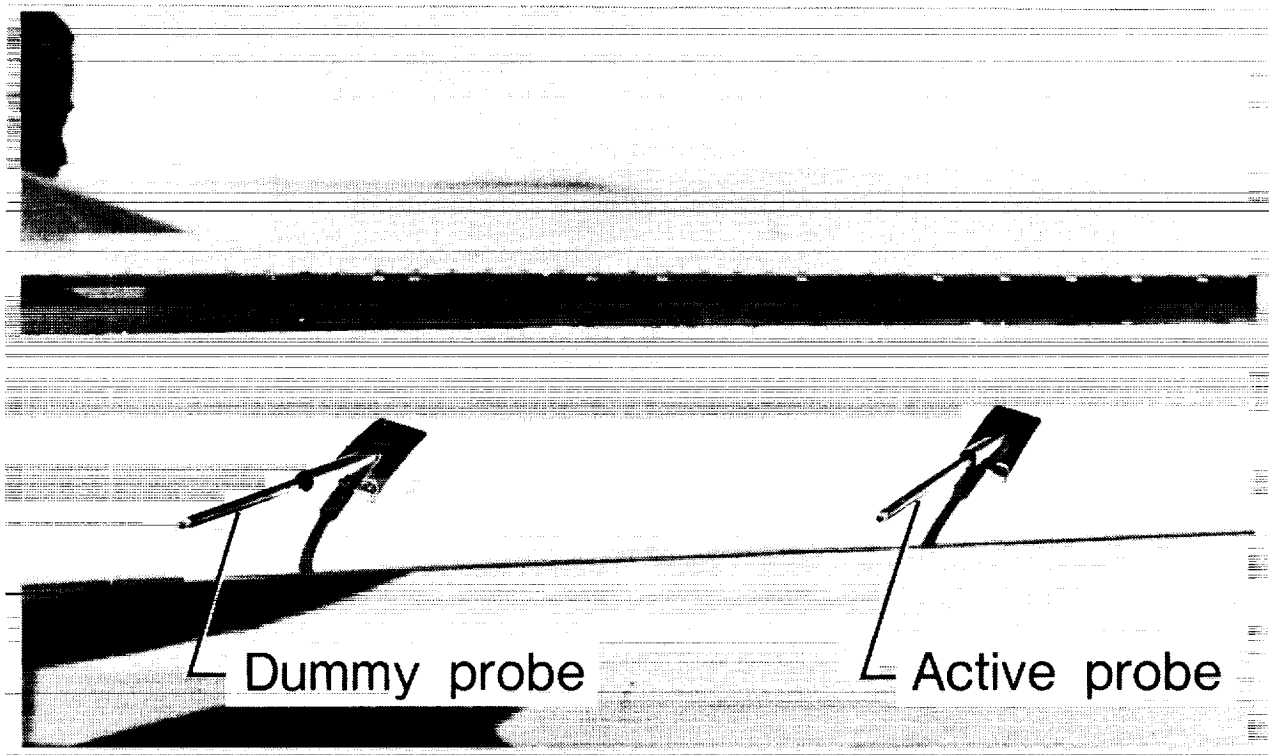

Figure 8

THREE-WIRE PROBE DATA ACQUISITION EQUIPMENT IN JETSTAR

A photograph of the three-wire hot-wire probe anemometry data acquisition system mounted in the NASA JETSTAR (fig. 9) was esentially the same acquisition system used in the flow quality test in the 0.3-m TCT (ref. 2). Three commercially available, constant temperature anemometers (CTAs) (DISA 55M system with 55M10CTA standard bridge) were used in both the wind tunnel and flight tests. The mean and RMS voltages were recorded by hand from the respective instruments during the flight. The signal conditioner was used to bandpass the signal (1.0 Hz lower frequency cutoff and 20 kHz upper frequency cutoff) and amplify the signal as required. The fluctuating and mean voltages were also recorded on a 28-track tape recorder used specifically for the flight test. The anemometers were operated by batteries in an effort to eliminate 60 Hz electrical noise present in the JETSTAR.
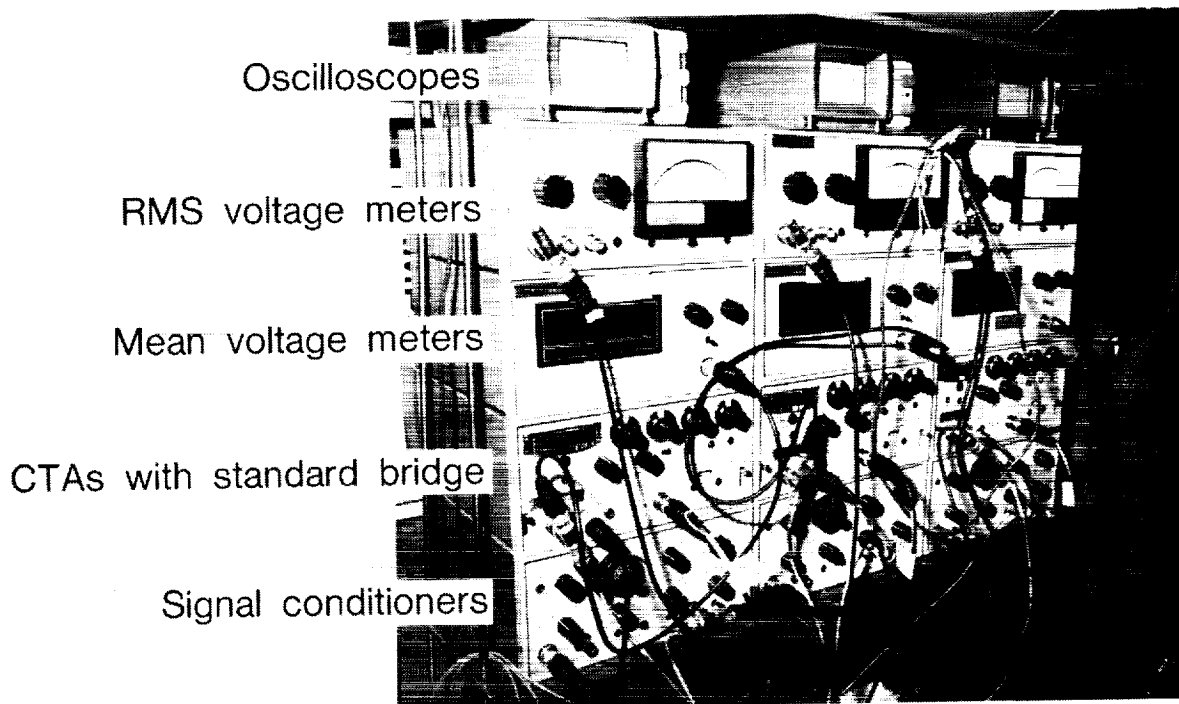

Figure 9

ATMOSPHERIC TURBULENCE FLIGHT DATA FROM THREE-WIRE PROBE

The RMS values of velocity, density, and total temperature, normalized by their respective free-stream quantities (fig. 10), were obtained with the three-wire hot-wire probe in a flight with the NASA JETSTAR in January 1982. The data were obtained at an altitude of 5000 feet over the Mojave Desert at Mach numbers of 0.2, 0.3, 0.4, and 0.5. The floor of the desert, relative to sea level, ranges from about 2200 to 2400 feet, which meant the flight altitude was about 2700 feet relative to the ground. The proximity of the desert floor, coupled with the high winds that generally prevail during the time of year of the flight, accounted for the rather high level of atmospheric turbulence (i.e., normalized RMS velocity fluctuation). The turbulence level and the extremely rough "ride quality" would put these measurements in the classification of "clear air turbulence."

Previous measurements of atmospheric turbulence (refs. 22 and 23), in terms of normalized RMS mass flow fluctuations, which were made at altitudes of 12, 29, and 39 thousand feet and Mach numbers from 0.28 to 0.80, indicated levels an order of magnitude less than those obtained with the three-wire probe (fig. 10). The density fluctuations (fig. 10) were somewhat lower than the velocity fluctuations, and the total temperature fluctuations were even lower. A comparison of the flight data in figure 10 with the wind tunnel data in figure 5 (from the identical hot wire probe) indicates that all three fluctuating quantities from the flight data are of at least an order of magnitude lower than the wind tunnel data.

M_∞	$R/ft \times 10^{-6}$	$\dfrac{\tilde{u}_\infty}{\bar{u}_\infty}$, %	$\dfrac{\tilde{\rho}_\infty}{\bar{\rho}_\infty}$, %	$\dfrac{\tilde{T}_{t,\infty}}{\bar{T}_{t,\infty}}$, %
0.2	1.24	0.6203	0.2029	0.07037
0.3	1.85	0.7014	0.2620	0.10630
0.4	2.47	0.4366	0.1339	0.08333
0.5	3.09	0.4503	0.1329	0.07231

Figure 10

SPECTRA OF VELOCITY, DENSITY, AND TOTAL TEMPERATURE FLUCTUATIONS FROM FLIGHT MEASUREMENTS OF ATMOSPHERIC TURBULENCE

Spectra were obtained from the flight measurements using the three-wire hot-wire probe at an altitude of 5000 feet for a Mach number of 0.5 and a Reynolds number about 3 million per foot (fig. 11). The slopes of the spectra for the velocity, density, and total temperature fluctuations appear to follow the expected -5/3 slope for a region of equilibrium turbulence. In this region, referred to as the inertial subrange, there is no production or dissipation and the spectra will have a -5/3 slope. The 60-Hz noise and its harmonics are present to some extent up to the limit of the spectra.
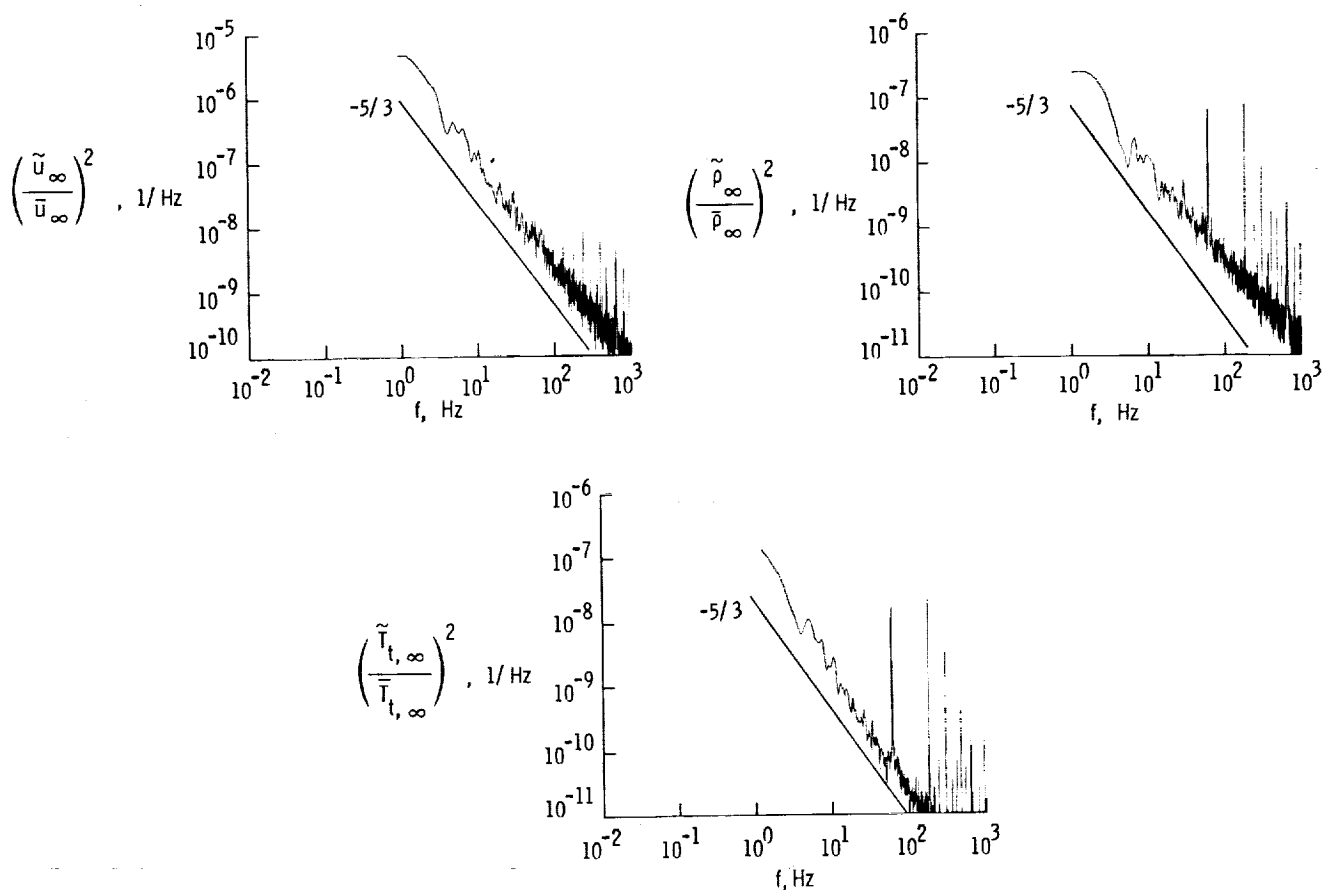
Figure 11

COMPARISON OF SEVERAL MEASUREMENTS OF ATMOSPHERIC TURBULENCE

The atmospheric turbulence measurements made with the three-wire hot-wire probe are compared with other atmospheric flight measurements (fig. 12) which include high and low altitude clear air turbulence, cumulus turbulence, and thunderstorm turbulence (ref. 24). The comparison, which is made in terms of the power spectral density versus reduced frequency, indicates good agreement between the three wire probe data and the other clear air turbulence data. All the data shown indicate a -5/3 slope over the entire range of reduced frequencies. The high and low altitude clear air turbulence data (ref. 24) was measured with sensors that had a low pass frequency cutoff of 16 Hz. In contrast, three-wire hot-wire probe data had a low pass frequency cutoff of 2500 Hz and thus extended out to reduced frequencies that were about two orders of magnitude higher than the other clear air turbulence data. It is interesting to note that the three wire data and the high and low altitude clear air turbulence data fall into a nearly linear band. The fact that the three sets of data "line up" is believed to be somewhat fortuitous.
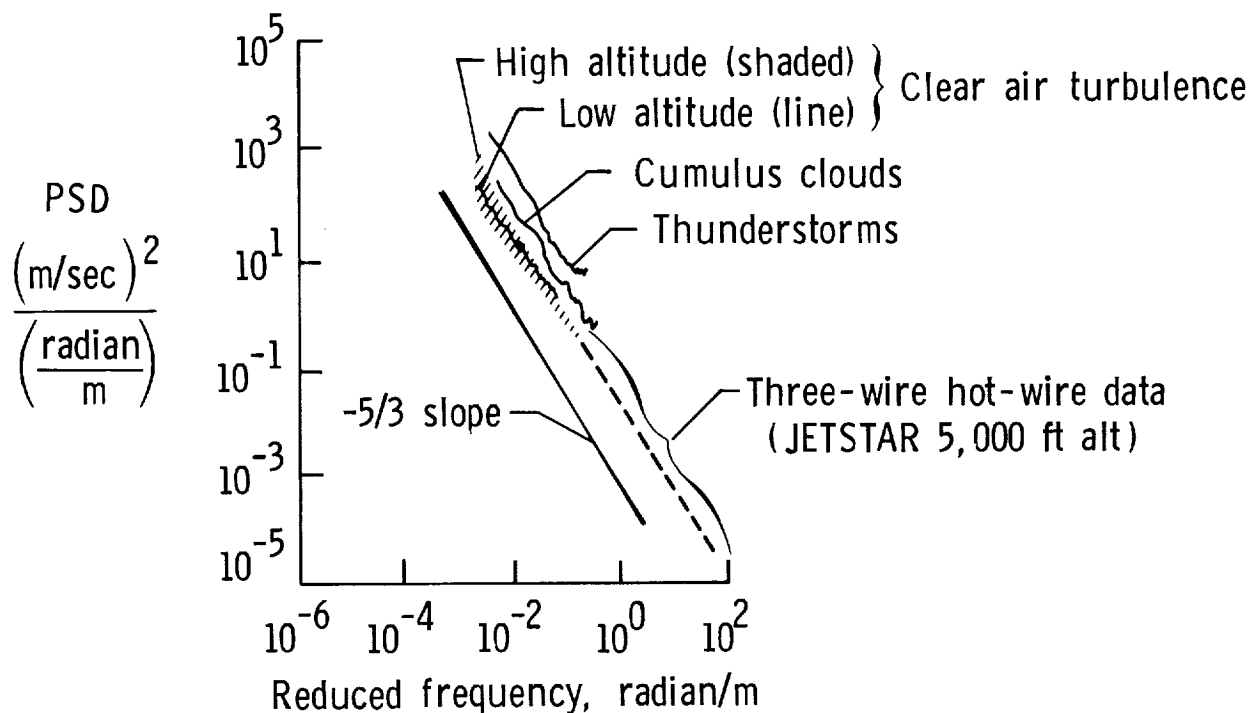

Figure 12